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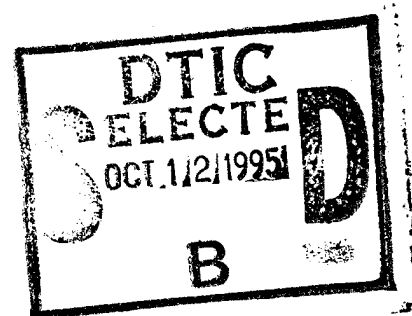


Modeling Micro-Terrain Using the Variable Resolution Terrain Model

Joseph K. Wald

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13. ABSTRACT (Maximum 200 words) <p>Digitized terrain data corresponding to a given geographical area are generally available in a rectangular grid at some fixed resolution. In the modeling and simulation of processes that interact with terrain, it is often desirable to model the terrain at a higher resolution. Unfortunately, it is impossible to discern terrain features smaller than the resolution of the data. In this report, the author uses the variable resolution terrain model to do the next best thing. He constructs a continuous terrain surface that matches the terrain data to a prescribed tolerance and simultaneously includes in that surface realistic terrain features smaller than the resolution of the data.</p>				
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1. Introduction

Digitized terrain data corresponding to a given geographical area are generally available in a rectangular grid at some fixed resolution (i.e., distance between neighboring (x,y)-coordinates). In the modeling and simulation of processes that interact with terrain, it is often true that the higher the resolution, the better. Thus, it is often desirable to be able to construct a model of a piece of terrain that has realistic terrain features that are smaller than the resolution at which the digitized data are available. We must use the term "realistic" rather than "real" since it is impossible to resolve any actual terrain feature smaller than the resolution of the data. For the purposes of this report, a "micro-terrain feature" is any terrain feature that is smaller than that fixed resolution, and "micro-terrain" is a collection of such micro-terrain features. A more precise mathematical definition of a terrain feature and the measure of its size is given in section 2.

In a previous report, the author described an algorithm that creates a smooth Variable Resolution Terrain (VRT) surface that matches a set of digitized terrain altitudes (DTAs) to within a prescribed tolerance at those (x, y)-coordinates at which the DTAs are defined.¹ In this report, that methodology is applied to the problem of adding micro-terrain to a set of DTAs.

The VRT model is described in section 2. The process of fitting a VRT surface to a set of DTAs is explained in section 3. In section 4, the basic methodology for adding micro-terrain is explained, with an example. Section 5 contains some thoughts on model validation procedures and future work.

2. The VRT Model

The VRT model, developed at the U.S. Army Ballistic Research Laboratory (now the U.S. Army Research Laboratory) in the early 1990s, is a model that represents basic topography as a continuous surface, capable of being viewed at any desired resolution.² This surface is the superposition of individual terrain features, or "hills" for simplicity, each of which is described by a closed form mathematical function that is continuous everywhere and has continuous partial derivatives almost everywhere. While examples of many different types of terrain have been constructed using the VRT model, they are all "generic" in the sense that they were developed from basic principles and do not represent

¹ Wald, Joseph K. "Solving the Inverse Problem in Terrain Modeling." ARL-TR-605, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1994.

² Wald, Joseph K. and Patterson, Carolyn J. "A Variable Resolution Terrain Model for Combat Simulation." BRL-TR-3374, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1992.

any particular piece of Earth topography. For generic terrain creation, the distribution of the sizes of the hills is based on the idea of self-similarity (i.e., invariance with respect to scale), which is embodied in the power law

$$D = Ks^{-2}, \quad (2.1)$$

in which s is a dimensionless scale factor associated with a hill, K is a constant that depends on terrain type, and D is the areal density of hills as a function of s . The choice of exponent in this power law ensures self-similarity in the density of terrain features. Integrating this power law produces the cumulative distribution function:

$$\int_{t=s_{\min}}^{t=s} Kt^{-2} dt = K(1/s_{\min} - 1/s). \quad (2.2)$$

There is, in practice, a range of scales, $[s_{\min}, s_{\max}]$, for which the power law holds. Thus, to build each hill, it is only necessary to draw a uniform random number u from the interval $(0, 1 - [s_{\min} / s_{\max}])$, with the hill scale factor being $s = s_{\min} / (1 - u)$. The location of the hill is randomly chosen in the desired area. The complete terrain surface is defined by the superposition of all of the hills, i.e.,

$$T(x, y) = \sum_{k=1}^N f_k(x, y). \quad (2.3)$$

The form of a single hill function, $f_k(x, y)$, is given by:

$$f_k(x, y) = s_k h_k \exp\left(-\left\{\frac{1}{s_k \rho_k} \left[\alpha_k E_k(x, y) + (1 - \alpha_k) M_k(x, y)\right]\right\}^{\sigma_k}\right), \quad (2.4a)$$

where

$$E_k(x, y) = \left[a_1(x - \xi_k)^2 - a_2(x - \xi_k)(y - \eta_k) + a_3(y - \eta_k)^2 \right]^{\frac{1}{2}}, \quad (2.4b)$$

$$a_1 = \varepsilon_k - \left(\varepsilon_k - \frac{1}{\varepsilon_k} \right) \cos^2 \lambda_k, \quad (2.4c)$$

$$a_2 = \left(\varepsilon_k - \frac{1}{\varepsilon_k} \right) \sin 2\lambda_k, \quad (2.4d)$$

and

$$a_3 = \varepsilon_k - \left(\varepsilon_k - \frac{1}{\varepsilon_k} \right) \sin^2 \lambda_k, \quad (2.4e)$$

and

$$M_k(x, y) = \max(|A_1(x, y)|, |A_2(x, y)|), \quad (2.4f)$$

where

$$A_1(x, y) = \varepsilon_k(x - \xi_k) \cos \lambda_k + \frac{1}{\varepsilon_k} (y - \eta_k) \sin \lambda_k, \quad (2.4g)$$

and

$$A_2(x, y) = \frac{1}{\varepsilon_k} (y - \eta_k) \cos \lambda_k - \varepsilon_k(x - \xi_k) \sin \lambda_k, \quad (2.4h)$$

This formulation is a substantial revision and extension of the original hill function definition.³ Varying the parameters α_k , ξ_k , η_k , h_k , ρ_k , ε_k , λ_k , σ_k , and s_k produces hills in a variety of sizes and shapes. While all of the parameters interact to some extent, roughly speaking, the parameters ξ_k and η_k govern the location of the "center" of the hill, h_k , ρ_k , and s_k govern the "height" and "width" of the hill, ε_k governs the "eccentricity" of the hill, λ_k governs the "orientation" of the hill, and σ_k governs the "slope" of the hill. The parameter α_k , whose value always lies in the interval $[0, 1]$, governs the shape of the horizontal cross section of the hill. When $\alpha_k = 1$, this cross section is elliptical. When $\alpha_k = 0$, the cross section is rectangular. For other values of α_k , the cross section has a more complex geometry. Rectangular hills are useful in the modeling of houses, roads, and other man-made objects as integral elements of the terrain.

3. Constructing a VRT Surface that Fits a Set of DTAs

The process of fitting a VRT surface to a set of DTAs has been documented.⁴ However, since that methodology plays an important part in the process of adding micro-terrain, it is appropriate to briefly describe it here.

The problem is to construct, in closed form, a surface $z = F(x, y)$, with the properties that $F(x, y)$ is continuous everywhere, has continuous partial derivatives $F_x(x, y)$ and $F_y(x, y)$ almost everywhere (i.e., everywhere except a set of measure zero), and that "matches" a given set of DTAs to within a prescribed tolerance, δ (i.e., for each DTA

³op. cit.

⁴ Wald, Joseph K. "Solving the Inverse Problem in Terrain Modeling." ARL-TR-605, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, October 1994.

point (x, y, d) , $|F(x, y) - d| \leq \delta$. [The advantage of obtaining such an $F(x, y)$ is clear. At virtually any point in the geographical area under consideration, both the terrain altitude and the slope of the terrain in any direction are obtained simply by evaluating $F(x, y)$, $F_x(x, y)$, and $F_y(x, y)$ at the desired (x, y) -coordinate.]

First, the DTAs are detrended by fitting a plane through them and subtracting the height of this plane from each of the DTAs. This produces a set of "residual" DTAs. Next, the residual DTA (x, y, d) of largest magnitude is found and a hill is constructed, the center of which is at or near (x, y) and the height of which is equal to or close to d . An iterative loop is used to compute the values of the VRT parameters in the construction of this hill. Here, the best hill is the one that leaves the smallest modified residual DTAs in the neighborhood of (x, y) when the hill is subtracted from the residual DTAs. This hill is subtracted from each of the residual DTAs to create a new set of residual DTAs. The new largest residual DTA is located and the hill fitting process is repeated until all of the residual DTAs are smaller in absolute value than δ . The VRT "fitting" surface, $F(x, y)$, is then defined to be the sum of the fitting plane and all of the fitting hills.

Note that since a pseudo-random number generator is used in the iterative loop, simply changing the random number seed will produce a slight variant for $F(x, y)$. In fact, there are an infinite number of surfaces that satisfy the conditions for $F(x, y)$.

4. Procedure for Adding Micro-Terrain

When constructing a generic VRT surface, micro-terrain is included simply by setting s_{\min} equal to the scale of the smallest desired terrain feature (in equation 2.2). However, adding micro-terrain to a set of DTAs is a more complicated matter. The first step is to construct a VRT surface, $F_1(x, y)$, that fits the DTAs to within a prescribed tolerance, δ . Next, empirical cumulative distributions are formed for the VRT parameters α_k , h_k , ρ_k , ϵ_k , λ_k , σ_k , and s_k from the parameters of the hills used to construct $F_1(x, y)$. The proportionality constant K (from equations 2.1 and 2.2) is estimated from the cumulative distribution of the values of the s_k parameter by fitting a curve of the same form as equation 2.2 to these values. Here, the value for s_{\min} is just the scale of the smallest terrain feature used to construct $F_1(x, y)$.

Having approximated the elements of the VRT model, the next step is to specify a new s_{\min} , denoted by s_{\min}^* , corresponding to the scale of the smallest micro-terrain feature desired, and then create a set of micro-hills by successively drawing uniform random numbers u from the interval $(0, 1 - [s_{\min}^* / s_{\min}])$, with the scale factor of a given hill being $s_{\min}^* / (1 - u)$. The location of each hill is randomly chosen in the area covered by

the VRT surface. The complete micro-terrain surface is defined by the superposition of all of the micro-hills, i.e.,

$$G(x, y) = \sum_{k=1}^{N_1} m_k(x, y), \quad (4.1)$$

where $G(x, y)$ is the "micro-surface" and each of the micro-hills, $m_k(x, y)$, has the same form as $f_k(x, y)$ in equation 2.4, with the parameters α_k , h_k , ρ_k , ϵ_k , λ_k , and σ_k randomly selected from the respective empirical cumulative distributions.

At this point, the sum $F_1(x, y) + G(x, y)$ is **not** formed. While it is true that this sum does approximate the DTAs (to some degree) and also contains micro-terrain, the condition $|F_1(x, y) + G(x, y) - d| \leq \delta$ may be violated for some (x, y, d) (i.e., the fit of $F_1(x, y)$ to the DTAs may have been disturbed by the addition of the micro-terrain). Instead, $F_1(x, y)$ is discarded and a *second* fitting surface is constructed, although in a slightly different manner. Instead of the flat plane, $z = 0$, construction starts with the micro-surface, $z = G(x, y)$, and to this surface a "detrending" plane and a sequence of empirically determined hills is added, using the same type of iterative loop as described in section 3. The product of this loop is a new approximating surface, $F_2(x, y)$. Since the loop termination condition is the same as before, the surface $S(x, y) = F_2(x, y) + G(x, y)$ satisfies the conditions for a fitting surface and also contains micro-terrain down to the desired scale.

This procedure works well when the DTAs represent a single terrain type. When the DTAs are extensive enough to include more than one terrain type, however, the empirical cumulative distributions should really be localized (i.e., the selection of parameters for the micro-hills should be based on the macro-hills in the same area). Also, the proportionality constant K may need to be localized.

Figures 1 through 3 illustrate the procedure for adding micro-terrain to a set of DTAs. A set of DTAs representing a 25-meter square of terrain from the National Training Center, Fort Irwin, California, was selected from a larger set of DTAs provided by the U.S. Army Topographic Engineering Center.⁵ The grid spacing for the DTAs is 5 meters, resulting in a total of 36 DTAs in the set. Figure 1 depicts the grid of DTAs. Clearly, any actual terrain feature contained in the piece of terrain from which the DTAs were extracted, but smaller than the grid size, cannot be "captured" by the DTAs. In figure 2, a VRT surface, constructed using the methodology described above, has been superimposed on the DTAs. The maximum deviation of the VRT surface from the DTAs (at

⁵F. Raye Norvelle, U.S. Army Topographic Engineering Center. Private Communication, March 1994.

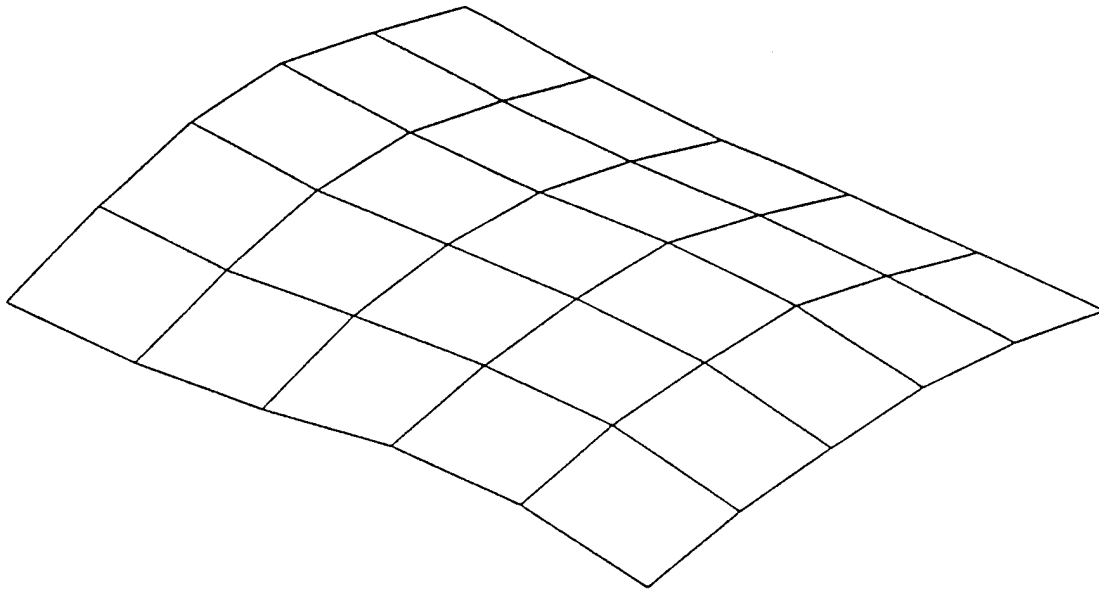


Figure 1. A 25-meter square - DTAs.

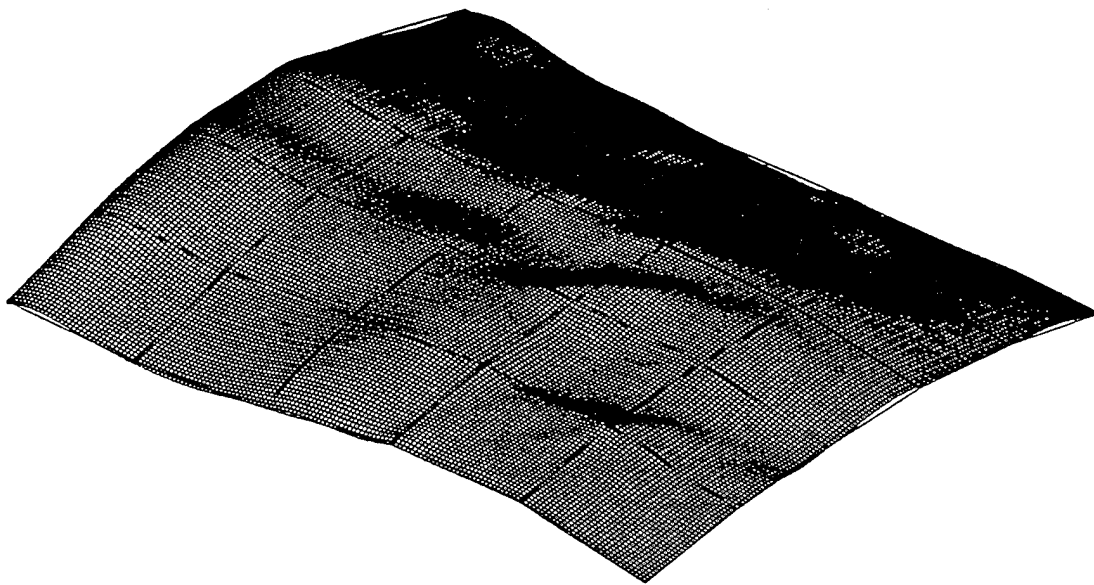


Figure 2. A 25-meter square - VRT surface.

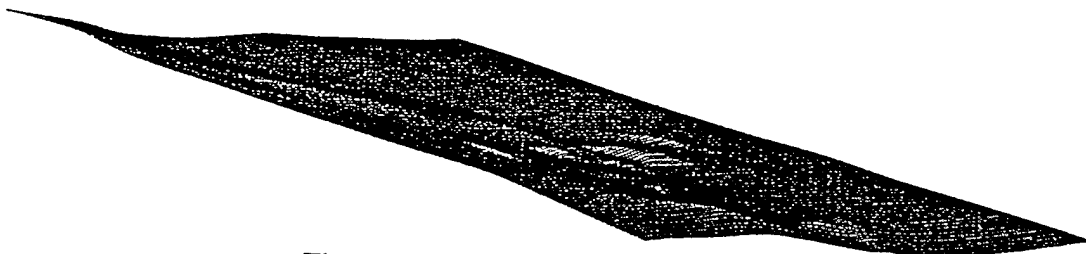


Figure 3. Close-up of a 5-meter square.

those (x,y) -coordinates at which DTAs were collected) is 8 centimeters and the average deviation is 4 centimeters. A total of 939 hills were constructed in the combined "micro/fitting" process, with micro-hills being constructed down to a scale of 1 centimeter. The construction of the VRT surface took slightly less than 2 seconds on a CRAY YMP computer. Figure 3 shows some of the smaller micro-hills in an "ant's-eye" view of a 5-meter square subset of the VRT surface.

5. Model Validation and Future Work

The fact that the VRT surface matches the DTAs to within the prescribed tolerance is easily checked by direct calculation. Since $S(x, y)$ is a finite sum of continuous functions with continuous derivatives of all orders almost everywhere, it inherits these properties.

However, the claim that the micro-terrain features are realistic is harder to verify, especially since the term "realistic" is not defined mathematically. The procedure for adding micro-terrain clearly depends strongly on the self-similarity assumption underlying the basic theory for VRT. This procedure works as long as the hills constructed lie within the range of scales for which that assumption is valid. Unfortunately, it is impossible to know in advance what that range is. There is, however, an important clue in the procedure that can help shed some light on this matter. Recall that the proportionality constant K is estimated from the empirical cumulative distribution of the values of the s_k parameter. The degree to which that empirical distribution matches the theoretical distribution of equation 2.2 gives a measure of how closely the real piece of terrain from which the DTAs were extracted matches an "ideal" VRT surface. If that match is good, then the assumption of self-similarity is valid, at least down to the scale corresponding to the resolution of the DTAs. If the match is not very good, there may still be a restricted range of scales for which a good match can be found.

In any case, to validate the micro-terrain creation model, it is necessary to define a process that demonstrates that for a given set of DTAs, the micro-terrain reflects, in some way, the small terrain features resident in the piece of terrain from which the DTAs were extracted. Of course, since DTAs are isolated points, it is impossible to make a direct comparison. In addition, it must be remembered that the model does not claim that it is recreating actual small terrain features (which are unknown below the resolution of the DTAs), but rather that the micro-terrain it is creating is representative of that *type* of terrain. These facts suggest that some type of statistical comparison is in order. For example, for a set of DTAs collected at a given resolution, it is possible to construct a VRT

surface with micro-terrain, $S(x, y)$, using a coarser subset of the DTAs. In fact, it is possible to construct many such surfaces, $S_i(x, y), i = 1, 2, \dots, L$. Then, for each DTA point, (x, y, d) , not used in the fitting process, compute the empirical distribution $z_i = S_i(x, y), i = 1, 2, \dots, L$. This provides a basis for comparison between the stochastic model and the data at the points for which a comparison is possible. At this point there are many different approaches that could be used to make the comparison. These will be investigated in future work. It should be pointed out that this validation methodology can also be considered as part of a design feedback loop, in which the characteristics of added micro-terrain can be adjusted to match a given type of terrain. Although this process is still limited to the resolution of the DTAs, it can give some measure of confidence when extrapolating to higher resolution.

By repeating the micro-terrain creation/validation process for large number of sets of DTAs from a given geographical area, it should eventually be possible to characterize terrain types in terms of the parameters of the VRT model. The undertaking of such a massive task is, however, well beyond the scope of the present work.

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